RADC-TR-77-219
Final Technical Report
February 1977

STUDY OF RADIATION-HARDENED QUARTZ PRODUCTION PROCESSES

IRT Corporation

Approved for public release;
distribution unlimited.

Sponsored by the Defense Nuclear Agency
Under Subtask Code Z99QAXTD040
Work Unit 02

ROME AIR DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
GRIFFISS AIR FORCE BASE, NEW YORK 13441

This report has been reviewed by the RADC Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be releasable to the general public, including foreign nations.

This technical report has been reviewed and approved for publication.

APPROVED: Ferdinand Euler

FERDINAND K. EULER
Project Engineer

APPROVED: Robert M. Barrett

ROBERT M. BARRETT
Director
Solid State Sciences Division

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) 9 Final rept. 10 Jun-31 Dec 76

19 REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

18 1. REPORT NUMBER RADC TR-77-219 ✓	2. GOVT ACCESSION NO.
	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) 6 Study of Radiation-Hardened Quartz Production Processes.	5. TYPE OF REPORT & PERIOD COVERED Final - 10 June 1976 - 31 December 1976
	14 6. PERFORMING ORG. REPORT NUMBER IRT-8151-003 ✓
7. AUTHOR(s) 10 D. P. Snowden, M. J. Treadaway, W. Hardwick, [redacted] T. F. Wrobel J. M. Flanagan	8. CONTRACT OR GRANT NUMBER(s) 15 F19628-76-C-0266 new
9. PERFORMING ORGANIZATION NAME AND ADDRESS IRT Corporation ✓ P. O. Box 80817 San Diego, California 92138	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 62704H CDNA41AA
11. CONTROLLING OFFICE NAME AND ADDRESS HQ, Defense Nuclear Agency Washington, D.C. 20305	12. REPORT DATE February 9, 1977 11 9 Feb 77
	13. NUMBER OF PAGES 41
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Deputy for Electronic Technology (RADC/ETSD) Hanscom AFB, MA 01731 Monitor: Ferdinand Euler/ETSD	15. SECURITY CLASS. (of this report) Unclassified 12 31 p.
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

16 CDNA, Z99QAXT 17 41, D040

18. SUPPLEMENTARY NOTES

This work sponsored by the Defense Nuclear Agency under Subtask Code Z99QAXTD040 and Work Unit 02

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Quartz resonators	Crystalline quartz
Radiation hardening	Quartz oscillators
Electron irradiation	Frequency stability
Quartz filters	Quartz production

404 388

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The results of an initial program performed by IRT Corporation in support of the RADC/DNA program "Radiation Hardened Quartz Process Investigations" are presented. Included are calculated depth-dose profiles in the resonator assuming 10-MeV electrons incident on the oscillator package to be used in the resonator evaluation program. Also presented are the results of irradiations of the oscillator package at the RADC facility. Effectiveness of a collimator in protecting oscillator and oven control electronics has been assessed and the over

Kun

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

20. ABSTRACT (Continued)

results of dose mapping throughout the electronics is presented. Scaling relationships relating dose in the resonator to the dose at an external reference point were developed. Irradiations of a working oscillator were performed to assess the extent of possible experimental anomalies that would impact the actual RADC measurements.

The results of the above tasks were evaluated in light of their impact on the RADC program and used to formulate working procedural and/or equipment choice suggestions. In addition, a preliminary study has been made of the hardness assurance requirements for quartz used in quartz crystal filters.

FOREWORD

Contributions to this report were made by W. H. Hardwick, D. P. Snowden, M. J. Treadaway, and T. F. Wrobel of IRT Corporation. In addition, T. M. Flanagan of Frequency and Time Systems, Incorporated developed the initial program (while at IRT) and subsequently served as a consultant on the program. The RADC personnel involved in these investigations were P. W. Pellegrini, F. K. Euler, and A. Kahan.

CONTENTS

SECTION 1

INTRODUCTION

High quality crystalline quartz devices are required by modern military communication and navigation systems. Since these systems must face the possibility of exposure to nuclear and/or space radiation, radiation tolerant quartz devices are needed. The requirements for quartz devices in systems where nuclear or space radiation can be encountered have led to investigations of radiation response of various types of quartz materials. In general, it is found that pure Z-growth swept synthetic quartz is the material of choice. Z-growth quartz can be obtained in several grades: electronic, optical, high Q and premium Q, and each grade can be swept. Quartz bars are graded by the manufacturer on the basis of process and performance specifications which have been written without consideration for the effects of radiation, and some latitude in processing and performance is allowed within each grade. In radiation tests, considerable variability in response has been seen for devices manufactured from the same grade of quartz. Both acceptable and grossly unacceptable performance has been observed within most grades. At the time of initiation of this program, the procedure for obtaining quartz for application to systems with radiation specifications was to:

(1) determine the grade of swept quartz which met system needs,

(2) order material and have devices fabricated,

(3) perform radiation tests on finished devices to determine acceptability or nonacceptability of the device.

This procedure is both costly and time consuming with six to ten months taken up by processing. In recognition of the need for an established and documented procedure for processing by the manufacturer and procuring by a systems builder, a hardness testing program was initiated for quartz or crystal devices. The goals of this program are (1) to produce specifications for growth and procurement of quartz which will consistently yield state-of-the-art performance when exposed to radiation, and (2) to make available

for other system use quartz bars found acceptable under this program. In addition, it is anticipated that recommendations for possible improvements in processing will result from this program.

The RADC/DNA "Quartz Radiation Hardness Assurance" program has been divided into various phases. This report describes the first phase of a hardness assurance program during which IRT Corporation has provided support to RADC primarily in the definition of the radiation-testing program. In addition, possible process requirements, process controls, and quality conformance tests have been suggested.

Recommendations on test geometry effects, critical to successful radiation tests have been made. IRT in cooperation with RADC personnel has carried out test irradiations at the RADC linear accelerator facility in order to characterize dose deposition in the oscillator package and provide RADC with input data to formulate an appropriate experimental configuration for use during oscillator measurements.

Finally, performance characteristics of quartz crystal filters have been surveyed by IRT in order to ascertain whether there exist any radiation hardness problems unique to filters. The latter effort was to identify if an additional program beyond the scope of the present program is necessary in order to provide hardness assurance guidelines for crystal filters.

SECTION 2

PROGRAM PLANNING

The processes involved in growing and sweeping quartz were reviewed in meetings at RADC and at Sawyer Research Products. As a result of these discussions, candidate controls can be postulated as a first step toward a hardness assurance specification for growth and sweeping.

<u>Growth and Processing Requirements</u>

Low aluminum impurity content
Slow growth rate
Vacuum deposited sweeping electrodes
Controlled atmosphere during sweeping
High-temperature sweeping

<u>Process Controls</u> (sliced from 100 percent of the bars)

IR absorption scan across Z-axis
Irradiation of slices after sweeping and optical examination

<u>Quality Conformance Tests</u>

Q^{-1} versus temperature
Lot sampling of resonators

The above listing is preliminary and other tests and inspections have been suggested for inclusion in each of the above categories. The list can be expected to change and become more specific as test data is evolved.

SECTION 3

EXPERIMENTAL GEOMETRY

The oscillator assembly chosen by RADC as the vehicle for resonator irradiation was Frequency Electronics Incorporated (FEI) model FE 2037B. As originally configured, this model contained the quartz resonator in an orientation such that the normal to the resonator disk was along the major axis of the oscillator package as illustrated in Figure 1. In order to avoid major irradiation of the oscillator circuits and oven-control electronics, it is necessary to irradiate the resonator along a diameter of the resonator disk. However, a simple one-dimensional energy loss calculation based on the Berger and Seltzer tables[1] indicates that it is likely that electrons incident on the package with an energy of 10 MeV will be stopped before traversing the entire resonator disk. Table 1 summarizes this calculation. Consequently, energy deposition in the resonator would be highly nonuniform, increasing rapidly at the end of the electron range. This would cause uncertainties in the interpretation of the frequency and Q changes. In addition, dose variations across the disk of the resonator can also be caused by scattering of the incident beam. Although detailed calculations of this effect were not made, it seems intuitively reasonable that these effects would be considerably greater for irradiation along the diameter of the disk than normal to it.

Several possible modifications were discussed with RADC such as: (1) use of higher energy radiation source, (2) removal or modification of part of the oscillator package which is responsible for degradation of beam energy, (3) use of a different oscillator for radiation testing, (4) irradiation with package axis at an angle ($\simeq$ 26 degrees) to the electron beam, and (5) 90-degree rotation of the resonator in the package. Discussions between RADC and FEI personnel indicated that recommendation (5) was feasible, allowing irradiation of the resonator disk in the direction of its thickness.

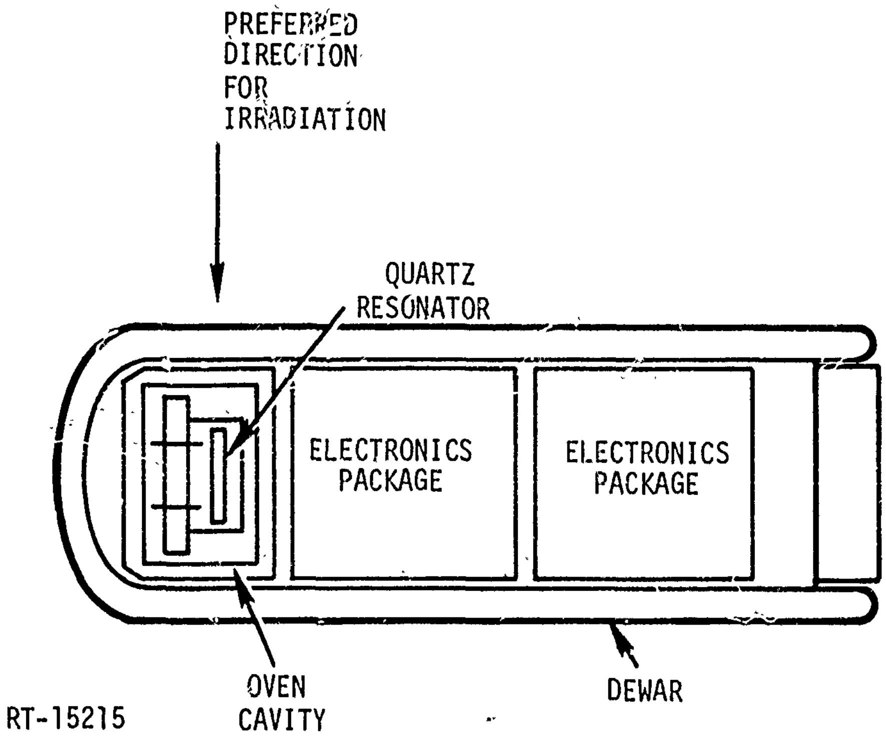

Figure 1. Oscillator package layout showing orientation of quartz resonator disk as originally mounted[2]

Table 1. Summary of Energy Degradation Calculation Through Oscillator Package

Material	Thickness (cm)	Density (gm/cm^3)	Electron Energy (MeV)
			10
Aluminum	0.0508	2.70	
			9.78
Pyrex	0.159	2.23	
			9.21
Vacuum	0.3175	0	
			9.21
Pyrex	0.159	2.23	
			8.65
Aluminum	0.533	2.70	
			6.34
Styrofoam	0.541	0.056	
			6.29
Copper	0.0254	8.92	
			5.93
Nitrogen	0.12	0.00125	
			5.93
Quartz	1.50	2.65	
			[a]

[a]Electrons are stopped in quartz.

SECTION 4

EXPERIMENTAL MEASUREMENTS

During test planning and coordinating meetings held in the early stages of this program, it became apparent that a number of questions relating to the test dosimetry could be best answered emprically. One such question is the relationship of the dose per pulse at some point external to the oscillator package to the dose at the resonator. Another is the impact of scattering, machine tuning and alignment on the dose ratio. In addition, the proximity of electronic components to the resonator required verification of the effectiveness of the collimation and shielding in order to optimize the life of the electronics.

The following is a description of the experiments performed by RADC and IRT personnel at the RADC Linac facility. These experiments were to examine the sensitivity of the dosimetry to geometry and tuning, to optimize the shielding of electronics and to work out test procedures which minimize the requirements for positioning the oscillator.

4.1 DOSIMETRY MEASUREMENTS

4.1.1 Silicon Calorimeter Dosimeters

Primary dosimetry was performed using silicon calorimeter dosimeters. These dosimeters are made of single-crystal silicon chips to which chromel-alumel thermocouples have been attached. The silicon chip measures 3.2 x 3.2 x 0.25 mm. In the center of one face of the chip, a 0.25-mm-diameter gold dot is alloyed. To this gold dot, a 25-μm chromel-alumel thermocouple is attached with a very small amount of indium alloy solder. The silicon chip is supported in the fixture by small blocks of styrofoam which also serve as thermal isolation.

Several factors were taken into account in the design of the silicon calorimeter. It is suspended by sytrofoam blocks, and the thermocouple was made from small-diameter wire for thermal isolation. The small amount of indium solder on the gold dot

is such that its mass is only a small perturbation on the silicon absorber (the mass ratio is 2 percent). Silicon is also a relatively good thermal conductor and will reach thermal equilibrium rapidly (< 0.1 second).

Radiation incident upon the silicon block results in a temperature rise which can be converted to energy deposition (dose) by the specific heat of silicon. The measurement is a direct determination of the average dose in the sample, independent of the type of radiation particle or its energy, and is traceable to NBS standards (NBS Circular 500, Part 1, 1952). The specific heat capacity for silicon is 0.169 ±0.001 cal/g-^{o}C at 25^{o}C. This can be directly converted to 7.08 x 10^4 rad(Si)/^{o}C by using the conversion factor 4.19 x 10^7 erg/cal and 10^{-2} g-rad/erg. The response of the chromel-alumel thermocouple at room temperature is 40 μV/^{o}C ±1 μV/^{o}C. Therefore, the response of our silicon calorimeter is 1757 rad(Si)/μV ±3 percent.

The largest source of error in using this type of calorimeter arises in the reading of the appropriate signals. The reading accuracy of the calibration is about 5 percent, and calorimeter response reading accuracy is approximately 10 percent (worst case); therefore, assuming that the errors propagate independently and that the remainder of the system has accuracies of approximately 3 percent, the total error in dose measurements becomes about 16 percent.

An analysis of the heat transfer characteristics between the silicon calorimeter and its environment has been performed on previous calorimeters constructed by IRT[3], and the dominant heat loss path was found to be conduction through the trapped air of the styrofoam. The calculated time constant agreed well with experimental values of about 10 seconds and is of sufficient duration to allow accurate reading of calorimeter deflection to be performed easily without the need for high-speed recording equipment.

One silicon dosimeter was mounted in an empty resonator package and was used to determine resonator dose. Other calorimeters were mounted at the input and output sides of the oscillator package. A multichannel dosimeter amplifier and recorder were used to display the output of these dosimeters simultaneously.

4.1.2 TLDs

Thermoluminescent dosimeters (TLDs) were used for measurement of total deposited dose at various locations in the package and its surroundings. RADC CaF_2-filled Teflon TLDs were used for most measurements and were read out immediately after being irradiated. In addition, in a few instances, IRT CaF_2 TLDs were also used

and read out approximately five days after irradiation. It had been determined previously that negligible bleaching of these dosimeters will occur over this time period. The largest difference noted between an IRT and RADC TLD was 30 percent and most differences were smaller than this. All TLDs were wrapped in aluminum foil prior to irradiation for equilibration of the dose deposited in the TLD.

4.1.3 PIN Diodes

The RADC PIN diode with a tantalum shield was routinely used to monitor the pulse shape of the Linac output. The diode was mounted behind the oscillator package for these measurements. In addition, the possibility of use of this diode in this location for routine dosimetry was evaluated. It was found that the diode signal did not track the resonator dose as measured with the internal Si calorimeter. When the dose was varied by insertion of a scattering plate at the Linac output, the PIN signal varied sublinearly with resonator dose. This effect is a direct result of the large energy loss in the oscillator package. As a result, a PIN is not suitable for routine dosimetry measurements.

4.2 RESONATOR POSITION

Measurements were made of the resonator location in the oscillator package in order to determine the optimum position of the package for irradiation.

In order to facilitate alignment, the center of the resonator was marked on the inner oscillator package.

4.3 COLLIMATION AND SHIELDING

Two collimator structures were evaluated experimentally. Collimator 1, provided by IRT, consisted of 5 cm of Aℓ backed by 2.5 cm of Pb and had a 2.5-cm-diameter collimation hole. Collimator 2, available at RADC, had 1.3 cm of Aℓ, 0.6 cm of Pb, and 0.6 cm of Aℓ and had a 1.3-cm-diameter collimation hole.

Using collimator 1 it was determined that dose deposited in the oscillator electronics nearest the resonator was 6 and 10 percent of the value at the resonator on the irradiating-beam-input side and output side, respectively (positions A and B, respectively, of Figure 2). The letters in this figure indicate the locations of the TLDs.

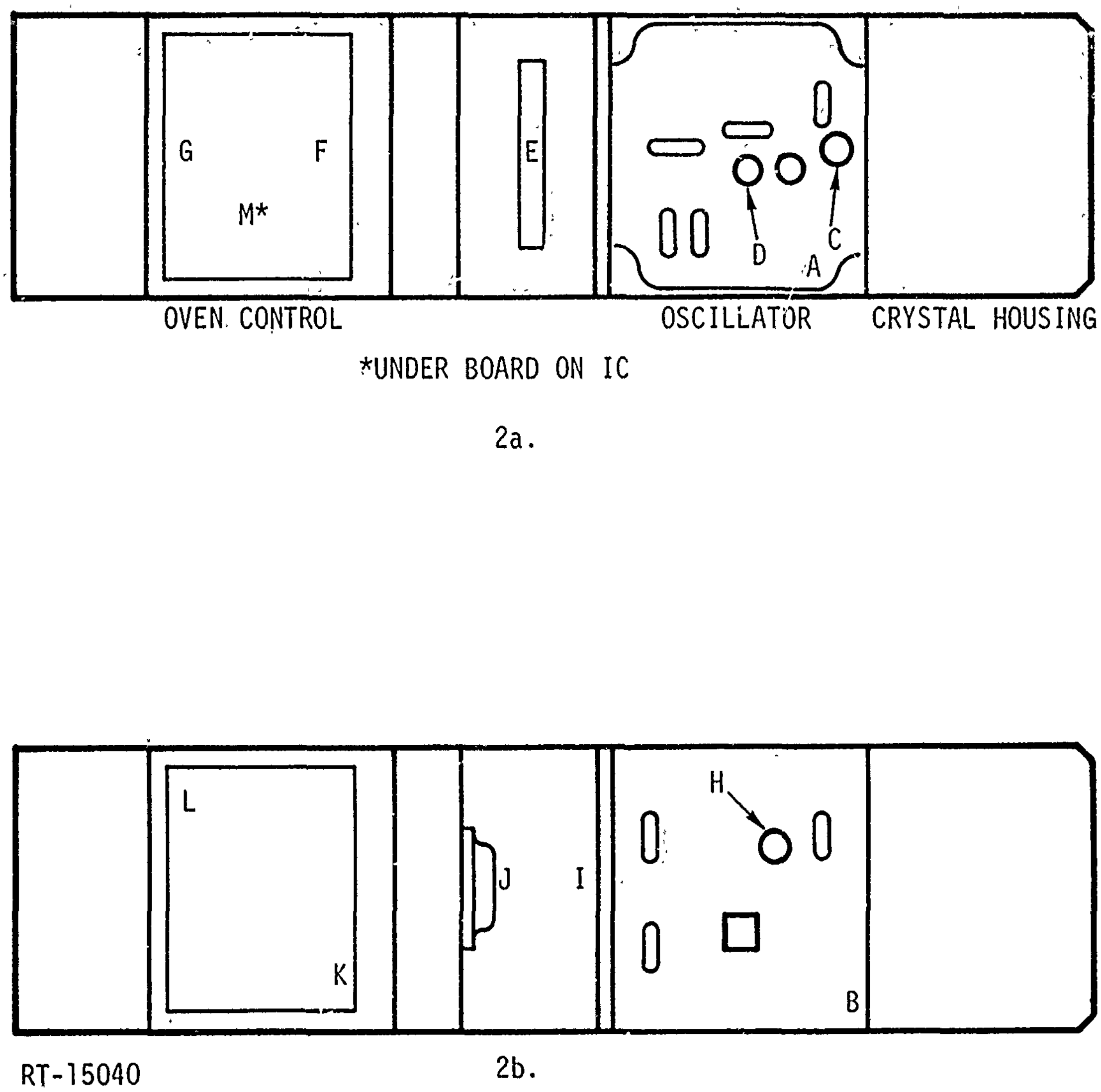

Figure 2. Schematic figure showing locations of electronics dose map. 2a: input side; 2b: output side

In an attempt to reduce this dose, collimator 2 was used. The dose at positions A and B was approximately the same with this collimator, ~7 percent of the value at the resonator.

Using collimator 2 it was determined that the dose at the resonator was independent of the position of the resonator within a circle of 6 mm diameter around the resonator center. It was therefore concluded that resonator alignment was not critical; adequate positioning can be obtained by visual alignment of the oscillator package with reference marks on the collimator plate.

Measurements of the transmitted dose behind both collimators were made by exposing TLDs on the back of the collimator with $\sim 5 \times 10^6$ rads incident. For Collimator 2, dose at the back was ~1 percent of the incident dose; for collimator 1, it was ~0.3 percent.

Based on the above measurements, it is recommended that the collimator to be built for RADC's resonator measurements be comparable in thickness to collimator 1, but utilize a collimation hole similar to that of collimator 2.

4.4 DOSE SCALING FACTORS

The ratio of dose at the resonator position to that at the input side of the oscillator package was determined by simultaneous measurements of the dose at these locations using silicon calorimeter dosimeters. These measurements were made with the resonator located at 10 cm and 40 cm from the output port of the Linac.

At 10 cm, this ratio was found to be 0.220 ±0.009 and at 40 cm was 0.290 ±0.011. The average dose per pulse in the resonator at the 10-cm position was 3.9 krads and at 40 cm was 260 rads for normal Linac operation using the 1.3-cm-diameter collimator.

In order to verify that the silicon calorimeter at the input was not affecting the dose deposited in the resonator, a series of measurements was made with TLDs at the input location for measurement of the input dose. To within the accuracy of the measurements, no difference was seen in the ratio of input to resonator dose.

The difference in the scaling factors at the two locations is explained by the $1/r^2$ dependence of the Linac output dose measured from a virtual focus point 5 cm behind the output point. (The internal and external dosimeters were separated by 3-cm.)

The calculated ratio should differ by a factor of 1.36 while the measured ratio differs by 1.32. The difference between these values is ~3 percent, less than the standard deviation of either of the scaling factors.

4.5 OSCILLATOR PACKAGE DOSE MAPPING

Dose deposited in the electronics package was measured with the oscillator at both 10- and 40-cm positions using TLDs. Figure 2 shows an outline diagram of the oscillator package and indicates the location of the points at which the dose was measured.

Table 2 summarizes the dose deposited at each of the locations defined in Figure 2 for unit dose deposited in the resonator.

It is noted that the dose at locations in the electronics well removed from the resonator is lower at the 10-cm position than at 40 cm. This indicates that not all of this dose is due to scattering from the resonator location, but that transmission through the stopping block also contributes. At the closer position, fewer electrons will be incident at any given off-axis position than at 40 cm. Consequently, use of the thicker stopping block as recommended above should further reduce the dose at 40 cm in the electronics.

Table 2. Dose[a] Deposited in Electronics Package at Locations Defined in Figure 2

TLD Position Location	Normalized Dose (10-cm position)	Normalized Dose (40-cm position)
A	1.4×10^{-1}	7.3×10^{-2}
B	4.9×10^{-2}	7.3×10^{-2}
C	4.3×10^{-2}	5.5×10^{-2}
D	2.3×10^{-2}	3.1×10^{-2}
E	8.4×10^{-4}	8.8×10^{-3}
F	8.4×10^{-4}	3.4×10^{-3}
G	$< 3 \times 10^{-4}$	2.1×10^{-3}
H	1.3×10^{-2}	3.4×10^{-2}
I	1.1×10^{-3}	1.1×10^{-2}
J	8.4×10^{-4}	9.2×10^{-3}
K	2.8×10^{-4}	3.5×10^{-3}
L	$< 3 \times 10^{-4}$	1.7×10^{-3}
M	$< 3 \times 10^{-4}$	2.1×10^{-3}

[a]Dose is relative to unit dose in the resonator using 1.3-cm-diameter collimator.

SECTION 5

RECOMMENDED EXPERIMENTAL SETUP

As a result of the tests at the RADC Linac, the following general guidelines were established for the experimental setup.

In order to obtain reproducibility, a 1.3-cm-thick aluminum base plate could be mounted on the fixed and movable tables at the irradiation locations and pinned to both tables. Reference to the Linac output port will be obtained by "pinning" to the fixed table and the movable table will be immobilized by "pinning" to the plate.

A stopping block collimator structure should be fabricated of 5 cm of aluminum backed by 2.0 cm of lead. A 1.3-cm-diameter collimator should be used. Standard locations at the 10 and 40-cm positions can be obtained either by pins in the aluminum plate which mate with holes in the collimator or by brackets or angles attached to the plate against which the stopping block is positioned.

The oscillator should be mounted "lying on its side" with the frequency adjustment screws pointing away from the axis of the Linac in a position in which they can be easily adjusted. The oscillator can rest on a shelf attached to the stopping block or to a separate stand mounted in a standard position behind the block.

After the Linac is initially tuned, final steering adjustments should be made by steering the beam through the collimator. This steering can also be checked during the day by sliding the oscillator away from the collimator so that it is completely behind the stopping block. A PIN diode attached to the stopping block and behind the oscillator when it is in the irradiation position can be used as a detector when the steering adjustments are made. The oscillator package can be moved manually, which would be entirely adequate. If more frequent adjustments will be needed, motorization of the oscillator position should be considered.

During initial tuning of the Linac at the beginning of the day, it will be feasible to leave the oscillator in the radiation room if necessary. The total dose in a location on the floor, near the end of the beam tube and behind lead bricks was found to be <200 rads during initial machine tuning.

Primary dosimetry can be made using a silicon calorimeter dosimeter fixed at the output side of the collimator. The dosimeter scaling factors given in paragraph 4.4 above would then be used to determine resonator dose.

Another possibility is to mount a silicon calorimeter inside the oscillator package at the position originally intended for a PIN diode. This will require a specially constructed calorimeter, and appropriate scaling factors for resonator dose as a function of position would have to be determined experimentally.

Although not absolutely mandatory, it is recommended that the dose scaling ratios and dose received in the electronics package be remeasured in the final experimental setup. This would verify the data presented here and also indicate any differences caused by the final experimental arrangement.

SECTION 6

INITIAL RESONATOR IRRADIATION

Initial measurements were made of the frequency offset induced by electron irradiation of a quartz resonator mounted in the FEI package used for the dosimetry characterization discussed above. The resonator was mounted in the package with the disk rotated 90 degrees as described above. The purpose of these tests was to check out the system and to uncover possible experimental problems.

Oscillator frequency was measured using the system previously set up and tested by RADC. The oscillator output was mixed with the output of the Hewlett-Packard Cesium Beam Frequency Standard, Model 5060A, and the frequency shift was determined with an FEI Frequency Error Analyzer and Digital Phase Comparator. The output of the error analyzer was displayed on a chart recorder. The response time of this system is such that frequency offset data is lost for the first several seconds after irradiation.

The behavior of the radiation-induced offset in this resonator was different than that usually seen where an initially large offset decays back to a smaller "steady-state" offset in about 15 to 20 minutes.[4] Instead, for this resonator, except for the first pulse of ~200 rads, the frequency offset was negative when the frequency error analyzer recovered (~5 seconds after the pulse) and continued to increase in a negative sense for 10 to 15 minutes before reaching a steady-state value. The offset caused by the first pulse was positive and decayed with time to a smaller positive value.

The magnitude of the oscillator offset during a Linac pulse, caused by other than radiation effects in the resonator was investigated. With a stopping block (5 cm aluminum backed with 2.5 cm of lead) in front of the collimator, the frequency offset was positive and varied from 1.0 to 2.2 parts in 10^{11} for a pulse which would have delivered ~150 rads without the stopping block (40-cm position). This offset was probably due to pickup in power supply leads, or possibly signal leads, which connected the oscillator to equipment in the measurement room. It is likely that this small frequency

offset could be reduced by use of low-pass filters on each of the power supply lines at the input to the oscillator package.

One pulse was also taken with the oscillator positioned behind the collimator so that the electronics package, at a position of ~ 2 cm from the resonator, would be irradiated. For this shot, $\Delta f/f = 2.8 \times 10^{-11}$ for a 150-rad pulse. Direct irradiation of the electronics in this position evidently contributes a small addition to the "spurious" frequency shift. However, since the dose to the electronics is reduced by a factor of 100 to 300 when the oscillator is positioned normally behind the collimator, this contribution should be entirely negligible.

One important consideration in the assessment of the long-term behavior of the oscillator after an irradiation pulse is the behavior of the oven and dewar assembly after the temperature excursion caused by the energy deposition of the pulse. A rough calculation of the thermal recovery time indicates it to be about 20 minutes and to be dominated by conduction down the dewar walls and the support structure of the internal electronics. Measurement by RADC of the oven current during and after an irradiating pulse tends to confirm this recovery time since the oven current was seen to change for at least this long.

Temperature shifts of a few millidegrees can cause frequency shifts of a few parts in 10^{11}, depending, of course, on the resonator temperature and frequency-temperature characteristics. Consequently, at least part of the oscillator frequency recovery may be affected by recovery of the resonator temperature. Additional data will be required to clarify this point.

SECTION 7

QUARTZ CRYSTAL FILTERS

Crystal filters have found many applications in analog and digital space systems and their radiation hardness has been investigated;[5] however, the question of how a user orders crystal filters which have radiation response comparable to filters used previously is a problem of hardness assurance. The question addressed here is whether the specifications used to ensure the hardness assurance of quartz resonators is sufficient to ensure the hardness of crystal filters. To address this question, it is necessary to identify those specifications used in the design of crystal filter networks which relate to the basic parameters of the bulk crystal material from which the filters are manufactured. The specifications include attenuation characteristics, phase and/or delay characteristics, bandwidth, spurious response, insertion loss, etc. It is then necessary to determine if the basic parameters of the bulk crystal material will be affected by radiation enough to adversely affect the filter response.

It must be recognized that circuit configurations of crystal filters are varied and often highly complex. Relating the change in the basic crystal parameters to a change in crystal filter response will be complicated by the circuit configuration, and therefore, an analysis on each configuration will be necessary in order to assess the response. Such an analysis is beyond the scope of this effort. However, in order to perform the analysis of an overall filter response, it is necessary to be able to predict the shift in the operation of each crystal element.

The response of the crystals can be analyzed in terms of the equivalent circuit shown in Figure 3, where C_p is the capacitance of quartz between electrodes; C_s is proportional to the elastance of the quartz; L_s is proportional to the mass of the quartz; R_s is proportional to the dissipation in the quartz. At series resonance, the crystal looks primarily resistive with a magnitude of R_s and the Q of the circuit is given by:

$$Q = \frac{X_{L_s}}{R_s} \quad . \tag{1}$$

The value of Q is quite large for most quartz materials (1×10^3 to 3×10^6 for 5 MHz fifth overtone resonators) and depends upon the quality of the quartz material.

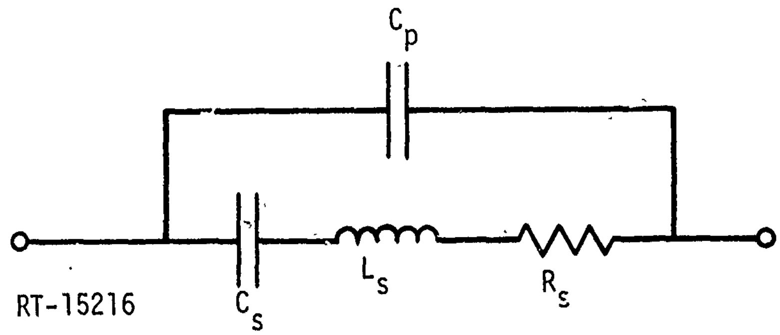

Figure 3. Electrical circuit equivalent of quartz resonator

Using the above information and a simplified filter circuit shown in Figure 4, the effect of inserting the crystal filter in the circuit may be analyzed.

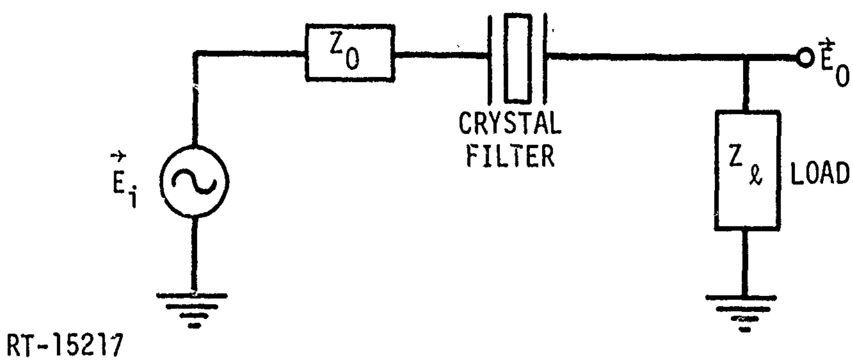

Figure 4. Simplified electrical circuit diagram for quartz filter

In order to realize maximum power transfer at resonance from the driver stage to the load, the load should be designed to be the complex conjugate of the source output impedance. This will put the loop current in phase with the source voltage which implies that the circuit looks resistive. The output voltage can be expressed as

$$\vec{E}_0 = \frac{\vec{E}_i \, \vec{Z}_\ell}{\vec{Z}_0 + \vec{Z}_\ell + \vec{Z}_{xtal}} \quad . \tag{2}$$

The denominator of this equation, at the resonant frequency, is composed of only the real portions of the impedances. Therefore,

$$\vec{E}_0 = \frac{\vec{E}_i \vec{Z}_\ell}{R_0 + R_\ell + R_s} \quad . \tag{3}$$

Without the crystal in the circuit, the output voltage, $\vec{E}_0'$, would be

$$\vec{E}_0' = \frac{\vec{E}_i \vec{Z}_\ell}{R_0 + R_\ell} \quad . \tag{4}$$

The insertion loss in dB of the crystal filter may now be calculated using Equations 3 and 4 as

$$\text{Insertion Loss (dB)} = 20 \log_{10} \left| \frac{\vec{E}_0}{\vec{E}_0'} \right| = 20 \log_{10} \frac{R_e}{R_e + R_s}$$

$$= 20 \log_{10} \frac{1}{1 + \frac{R_s}{R_e}} \quad . \tag{5}$$

where $R_e = R_0 + R_\ell$. From Equation 5, it can be seen that if the insertion loss is to remain low, then the ratio of R_s to R_e must be kept small. Radiation data on quartz resonators indicate that at very modest ionizing dose levels, the value of R_s may vary significantly for some types of quartz crystals.[6] Annealing does occur over a time period of approximately one second; however, in the case of natural quartz, some permanent changes may occur.

The consequences of the increase in the insertion loss will be a decrease in the signal level, thus reducing the signal-to-noise ratio in the circuit. Another detrimental effect (seen from Equation 1) is the reduction of Q as R_s increases, resulting in a broadening of the signal passband.

Also,

$$Q = f_0/\Delta f \quad , \tag{6}$$

where f_0 is the center frequency and Δf is the 3-dB bandwidth. This may result in an increase in the noise level which will reduce the signal-to-noise ratio further. Whether or not this decrease in the signal-to-noise ratio will be detrimental to circuit operation, will depend upon circuit application and design margins.

There are other radiation effects on quartz that can contribute to the reduction of signal-to-noise ratio. A shift in the resonant frequency of the resonators after exposure to ionizing radiation has been observed.[5] This is manifested as an initial transient offset which generally anneals at least partially and a residual permanent offset. For crystal filters designed with very high Q crystal requirements, this shift in resonant frequency may cause an out-of-tolerance shifting in the overall bandpass characteristics. This shift in the frequency response will cause the signal to operate on the edge of the bandpass characteristic curve which will result in a phase shift in the output voltage. In timing applications, this phase shift may result in significant timing error by the time the transient shift has annealed to the post-irradiation value.

The above-mentioned radiation effects are of concern for the circuit designer when there is need for very narrow band crystal filters (BW = 10's to 100's Hz) or if a wide band filter is designed using a number of narrow band units. The swept synthetic quartz crystals used in the construction of hardened quartz resonators are a better choice for those critical applications in which very narrow bandpass is needed in the design.

From this study, we see that the same parameters which affect the performance of quartz resonators also control the behavior of crystal filters. Consequently, hardness assurance criteria for resonators will, in general, be valid for filters, although limits on parameter shifts may be somewhat different. Detailed analysis of specific critical filter circuits would be necessary to determine the precise requirements on quartz hardness. It seems likely, however, that these requirements will not be more stringent than those for resonators.

One area on which we have not found specific experimental or analytical work is the relationship between the radiation-induced changes in Q and R_s for fifth harmonic

AT-cut resonators used in oscillators and those in the fundamental mode resonators used for filters. This relationship could have important consequences on the radiation hardness of filters and should be addressed further.

REFERENCES

1. M. J. Berger and S. M. Seltzer, "Tables of Energy Losses and Ranges of Electrons and Positrons," National Aeronautics and Space Administration, NASA SP-3012 (1964).

2. M. B. Bloch and John L. Denman, "Further Development on Precision Quartz Resonators," Proc. 28th Annual Symposium Freq. Control, 73 (1974).

3. T. F. Wrobel and R. A. Berger, "Silicon Calorimeter Systems for Gamma- and Electron-Beam Radiation Dosimetry," IEEE Transactions on Nuclear Science NS-22, 2314 (1975).

4. J. C. King and H. H. Sander, "Transient Change in Q and Frequency of AT-Cut Quartz Resonators Following Exposure to Pulsed X-Rays," IEEE Transactions on Nuclear Science NS-20, 117 (1973).

5. Private Communication, R. Kingsland, TRW.

6. T. M. Flanagan and T. F. Wrobel, "Radiation Effects in Sweep Synthetic Quartz," IEEE Transactions on Nuclear Science NS-16, 130 (1969).

PRECEDING PAGE BLANK-NOT FILMED

DISTRIBUTION LIST

DEPARTMENT OF DEFENSE

Defense Communication Engineer Center
1860 Wiehle Ave
Reston, VA 22090
Attn: Code R320 C W Bergman
Attn: Code R410 J W McClean

Director
Defense Communications Agency
Washington DC 20305
Attn: Code 540.5
Attn: Code 930 M I Burgett Jr

Defense Documentation Center
Cameron Station
Alexandria VA 22314
Attn: TC

Director
Defense Intelligence Agency
Washington DC 20301
Attn: DS-4A2

Director
Defense Nuclear Agency
Washington DC 20305
Attn: TITL Tech Library
Attn: DDST
Attn: RAEV
Attn: STVL

Dir of Defense Rsch & Engineering
Department of Defense
Washington DC 20301
Attn: S&SS (OS)

Commander
Field Command
Defense Nuclear Agency
Kirtland AFB NM 87115
Attn: FCPR

Director
Interservice Nuclear Weapons School
Kirtland AFB NM 97115
Attn: Document Control

Director
Joint Strat Tgt Planning Staff JCS
Offutt AFB Omaha NB 68113
Attn: JLTW-2

Chief
Livermore Division Fld Command DNA
Lawrence Livermore Laboratory
P.O. Box 808
Livermore CA 94550
ATTN: FCPRL

Director
National Security Agency
Ft. George G. Meade MD 20755
Attn: O O Van Gunten R-425
Attn: TDL

DEPARTMENT OF ARMY

Project Manager
Army Tactical Data Systems
US Army Electronics Command
Fort Monmouth NJ 07703
Attn: DRCPN-TDS-SD
Attn: DWAINE B. Huewe

Commander
BMD System Command
P.O. Box 1500
Huntsville AL 35807
Attn: BDMSC-TEN Noah J. Hurst

Commander
Frankford Arsenal
Bridge and Tacony Sts
Philadelphia PA 19137
Attn: SARFA FCD/M. Elnick

Commander
Harry Diamond Laboratories
2800 Powder Mill Road
Adelphi MD 20783
Attn: J. Halpin
Attn: DRXDO-RB/J. R. Miletta
Attn: DRXDO-RCC/J. E. Thompkins
Attn: DRXDO-NP/F. N. Wimenitz
Attn: DRXDO-EM/R. Bostak
Attn: DRXDO-RC/R. B. Oswald Jr.
Attn: DRXDO-EM/R. E. McCoskey
Attn: DRXDO-TI/Tech Library
Attn: J. McGarrity

Commanding Officer
Night Vision Laboratory
U S Army Electronics Command
Fort Belvoir VA 22060
Attn: Capt. Allan S. Parker

US Energy Research & Dev Admin
Albuquerque Operations Office
P. O. Box 5400
Albuquerque NM 87115
Attn: Doc Con for WSSB

OTHER GOVERNMENT

Department of Commerce
National Bureau of Standards
Washington, DC 20234
Attn: Judson C. French

DEPARTMENT OF DEFENSE CONTRACTORS

Aerojet Electro-Systems Co.
Div of Aerojet-General Corp.
P. O. Box 296, 1100 W. Hollyvale Dr
Azusa, CA 91702
Attn: T. D. Hanscome

Aero ipace Corp.
P. O. Box 92957
Los Angeles CA 90009
Attn: John Ditre
Attn: Irving M. Garfunkel
Attn: S. P. Bower
Attn: Julian Reinheimer
Attn: L. W. Aukerman
Attn: Library
Attn: William W. Willis

Analog Technology Corp.
3410 East Foothill Boulevard
Pasadena CA 91107
Attn: J. J. Baum

AVCO Research & Systems Group
201 Lowell St
Wilmington MA 01887
Attn: Research Lib/A830 Rm 7201

BDM Corp.
7915 Jones Branch Drive
McClean VA 22101
Attn: T. H. Neighbors

BDM Corporation
P O Box 9274
Albuquerque International
Albuquerque NM 87119
Attn: D. R. Alexander

Bendix Corp.
Communication Division
East Joppa Road
Baltimore MD 21204
Attn: Document Control

Bendix Corp.
Research Laboratories Division
Bendix Center
Southfield MI 48075
Attn: Mgr Prgm Dev/D. J. Niehaus
Attn: Max Frank

Boeing Company
P. O. Box 3707
Seattle, WA 98124
Attn: H. W. Wicklein/MS 17-11
Attn: Itsu Amura/2R-00
Attn: Aerospace Library
Attn: R. S. Caldwell/2R-00
Attn: Carl Rosenberg/2R-00

Booz-Allen and Hamilton, Inc.
106 Apple Street
Tinton Falls NJ 07724
Attn: Raymond J. Chrisner

California Institute of Technology
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena CA 91103
Attn: J. Bryden
Attn: A. G. Stanley

Charles Stark Draper Laboratory Inc.
555 Technology Square
Cambridge MA 02139
Attn: Kenneth Fertig
Attn: Paul R. Kelly

Cincinnati Electronics Corp.
2630 Glendale - Milford Road
Cincinnati OH 45241
Attn: Lois Hammond
Attn: C. R. Stump

Control Data Corporation
P. O. Box 0
Minneapolis, MN 55440
Attn: Jack Meehan

Cutler-Hammer, Inc.
AIL Division
Comac Road
Deer Park NY 11729
Attn: Central Tech Files/A. Anthony

AF Avionics Laboratory, AFSC
Wright-Patterson AFB OH 45433
Attn: DHE/H. J. Hennecke
Attn: DHM/C. Friend
Attn: DH/Ltc. McKenzie
Attn: AAT/M. Friar

Commander
ASD
Wright-Patterson AFB OH 45433
Attn: ASD/ENESS/P. T. Marth
Attn: ASD-YH-EX/Ltc. R. Leverette
Attn: ENACC/R. L. Fish

Hq ESD
Hanscom AFB MA 01731
Attn: YSEV

Hq ESD
Hanscom AFB MA 01731
Attn: YWET

Commander
Foreign Technology Division, AFSC
Wright-Patterson AFB OH 45433
Attn: FTDP

Commander
Rome Air Development Center, AFSC
Griffiss AFB NY 13440
Attn: RBRP/C. Lane
Attn: RBRAC/T. L. Krulac

Commander
RADC/Deputy for Electronic Technology
Hanscom AFB MA 01731
Attn: ES/A. Kahan
Attn: ES/B. Buchanan
Attn: ES/R. Dolan

SAMSO/DY
Post Office Box 92960
Worldway Postal Center
Los Angeles CA 90009
Attn: DYS/Capt. E. Merz

SAMSO/IN
Post Office Box 92960
Worldway Postal Center
Los Angeles CA 90009
Attn: IND/I. J. Judy

SAMSO/MN
Norton AFB CA 92409
Attn: MNNH

SAMSO/RS
Post Office BOX 92960
Worldway Postal Center
Los Angeles CA 90009
Attn: RSMG/Capt. Collier
Attn: RSSE/Ltc. K. L. Gilbert

SAMSO/SK
Post Office Box 92960
Worldway Postal Center
Los Angeles CA 90009
Attn: SKF/P. H. Stadler

SAMSO/SZ
Post Office Box 92960
Worldway Postal Center
Los Angeles CA 90009
Attn: SZJ/Capt. J. H. Salch

Commander in Chief
Strategic Air Command
Offutt AFB NB 68113
Attn: XPFS/Maj. B. G. Stephan
Attn: NRI-STINFO Library

US ENERGY RSCH & DEV ADMIN

University of California
Lawrence Livermore Laboratory
P.O. Box 808
Livermore CA 94550
Attn: L. Cleland/L-156
Attn: R. L. Ott/L-531
Attn: Tech Info Dept/L-3
Attn: H. Kruger/L-96
Attn: J. E. Keller Jr. /L-125

Los Alamos Scientific Laboratory
P.O. Box 1663
Los Alamos NM 87545
Attn: Doc Con for B. W. Noel
Attn: Doc Con for J. A. Freed

SANDIA Laboratories
P.O. Box 5800
Albuquerque NM 87115
Attn: Doc Con for Org 2110/J A Hood
Attn: Doc Con for 3141 Sandia Rpt Coll
Attn: Doc Con for Org 2140/R. Gregory

Commander Officer
Naval Avionics Facility
21st & Arlington Ave
Indianapolis IN 46218
Attn: Branch 942/D. J. Repass

Commander
Naval Electronic Systems Command Hqs
Washington DC 20360
Attn: Code 5032/C. W. Neill
Attn: Code 504511/C. R. Suman
Attn: Code 50451
Attn: PME 117-21
Attn: ELEX 05323/C. F. Watkins

Commanding Officer
Naval Intelligence Support Ctr
4301 Suitland Road, Bldg. 5
Washington DC 20390
Attn: NISC-45

Director
Naval Research Laboratory
Washington, DC 20375
Attn: Code 4004/E. L. Brancato
Attn: Code 2627/D. R. Folen
Attn: Code 5210/J. E. Davey
Attn: Code 6440/G. Sigel
Attn: Code 601/E. Wolicki
Attn: Code 6631/J. C. Ritter
Attn: Code 5216/H. L. Hughes
Attn: Code 7701/J. D. Brown

Commander
Naval Sea Systems Command
Navy Department
Washington DC 20362
Attn: SEA-9931/R. B. Lane
Attn: SEA-9931/S. A. Barham

Officer-in-Charge
Naval Surface Weapons Center
White Oak, Silver Spring, MD 20910
Attn: Code WA52/R. A. Smith
Attn: Code WA501/Navy Nuc Prgms Off
Attn: Code WA50

Commander
Naval Weapons Center
China Lake CA 93555
Attn: Code 533 Tech Library

Commanding Officer
Naval Weapons Evaluation Facility
Kirtland AFB Albuquerque NM 87117
Attn: Code ATG/Mr. Stanley

Commanding Officer
Naval Weapons Support Center
Crane, IN 47522
Attn: Code 7024/J. Ramsey
Attn: Code 70242/J. A. Munarin

Commanding Officer
Nuclear Weapons TNG Center Pacific
Naval Air Station, North Island
San Diego CA 92135
Attn: Code 50

Director
Strategic Systems Project Office
Navy Department
Washington DC 20376
Attn: SP 2701/J. W. Pitsenberger
Attn: NSP-2342/R. L. Coleman
Attn: NSP-27331/P. Spector

DEPARTMENT OF THE AIR FORCE

RADC/Deputy for Electronic Technology
Hanscom AFB MA 01731
Attn: ET/Stop 30/E. Cormier
Attn: ES/Stop 30/F. Shepherd
Attn: ES/Stop 30/E. A. Burke

AF Institute of Technology, AU
Wright-Patterson AFB OH 45433
Attn: ENP/C. J. Bridgman

AF Materials Laboratory, AFSC
Wright-Patterson AFB OH 45433
Attn: LTE

AF Weapons Laboratory, AFSC
Kirtland AFB NM 87117
Attn: ELS
Attn: ELA
Attn: ELP Tree Section
Attn: ELP/J. Nichols
Attn: NTS
Attn: ELXT
Attn: DEX

AFTAC
Patrick AFB FL 32925
Attn: TFS/Maj. M. F. Schneider

Commander
Picatinny Arsenal
Dover NJ 07801
Attn: SMUPA-ND-D-B/E. J. Arber
Attn: SARPA-FR-F/L. Avrami
Attn: SMUPA-ND-N-E
Attn: SMUPA-FR-S-P
Attn: SARPA-ND-C-E/A. Nordio
Attn: SMUPA-ND-W

Commander
Redstone Scientific Information Center
US Army Missile Command
Redstone Arsenal AL 35809
Attn: Chief, Documents

Secretary of the Army
Washington DC 20310
Attn: ODUSA or D. Willard

Director
Trasana
White Sands Missile Range NM 88002
Attn: ATAA-EAC/F. N. Winans

Director
US Army Ballistic Research Labs
Aberdeen Proving Ground, MD 21005
Attn: DRXBR-VI/J. W. Kinch
Attn: DRXBR-VL/R. L. Harrison
Attn: DRXBR-AM/W. R. Vanantwerp
Attn: DRXRD-BVL/D. L. Riggoti

Chief
US Army Communications Systems Agency
Fort Monmouth NJ 07703
Attn: SCCM-AD-SV/Library

Commander
US Army Electronics Command
Fort Monmouth NJ 07703
Attn: DRSEL-TL-MD/G. K. Gaule
Attn: DRSEL-TL-IR/E. T. Hunter
Attn: DRSEL-CE/T. Preiffer
Attn: DRSEL-GG-TD/W. R. Werk
Attn: DRSEL-TL-ND/S. Kronenbey
Attn: DRSEL-PL-ENV/H. A. Bomke

Commandant
US Army Engineer School
Ft. Belvoir VA 22060
Attn: ATSE-CTD-CS/C. S. Grazier

Commander-in-Chief
US Army Europe & Seventh Army
APO New York 09403
(Heidelberg)
Attn: ODCSE-E AEAGE-PI

Commandant
US Army Field Artillery School
Fort Sill OK 73503
Attn: ATSFA-CTD-ME/H. Moberg

Commander
US Army Material Dev & Readiness CMD
5001 Eisenhower Ave
Alexandria VA 22333
Attn: DRCDE-d/L. Flynn

Commander
US Army Missile Command
Redstone Arsenal AL 35809
Attn: DRSMI-RGD/V. Ruwe
Attn: DRSMI-RRR/F. P. Gibson
Attn: DRCPM-PE-EA/W. O. Wagner

Chief
US Army Nuc & Chemical Surety GP
Bldg 2073, North Area
Ft Belvoir VA 22060
Attn: MOSG-ND/Maj. S. W. Winslow

Commander
US Army Nuclear Agency
7500 Backlick Road
Building 2073
Springfield VA 22150
Attn: ATCN-W/Ltc. L. A. Sluga

Commander
US Army Tank Automotive Command
Warren MI 48090
Attn: DRCPM-GCM-SW/L. A. Wolcott

Commander
White Sands Missile Range
White Sands Missile Range NM 88002
Attn: STEWS-TE-NT/M. P. Squires

DEPARTMENT OF NAVY

Chief of Naval Research
Navy Department
Arlington VA 22217
Attn: Code 427

Dikewood Industries, Inc.
1009 Bradbury Drive, S.E.
Albuquerque, NM 87106
Attn: L. Wayne Davis

E-Systems, Inc.
Greenville Division
P.O. Box 1056
Greenville TX 75401
Attn: Library 8-50100

Effects Technology, Inc.
5383 Hollister Avenue
Santa Barbara CA 93111
Attn: Edward J. Steele

Exp & Math Physics Consultants
P.O. Box 66331
Los Angeles CA 90066
Attn: Thomas M. Jordan

Fairchild Camera & Instrument Corp.
464 Ellis St
Mountain View CA 94040
Attn: Sec Dept for 2-233 D. K. Myers

Fairchild Industries, Inc.
Sherman Fairchild Technology Center
20301 Century Boulevard
Germantown, MD 20767
Attn: Mgr Config Data & Standards

Florida, University of
P.O. Box 284
Gainesville FL 32601
Attn: Patricia B. Rambo
Attn: D. P. Kennedy

Ford Aerospace & Communications Corp.
3939 Fabian Way
Palo Alto, CA 94303
Attn: Edward R. Hahn/MS-X22
Attn: Donald R. McMorrow/MS-G30
Attn: Samuel R. Crawford/MS-531

Ford Aerospace & Comm Operations
Ford & Jamboree Roads
Newport Beach CA 92663
Attn: F. R. Poncelet Jr.
Attn: Ken C. Attinger
Attn: Tech Info Section

Franklin Institute, The
20th St and Parkway
Philadelphia PA 19103
Attn: Ramie H. Thompson

Garrett Corporation
P.O. Box 92248, 9851 Sepulveda Blvd
Los Angeles CA 90009
Attn: Robert E. Weir/Dept 93-9

General Dynamics Corp.
Electronics Div Orlando Operations
P.O. Box 2566
Orlando, FL 32802
Attn: D. W. Coleman

General Electric Company
Space Division
Valley Forge Space Center
Goddard Blvd King of Prussia
P.O. Box 8555
Philadelphia PA 19101
Attn: Larry I. Chasen
Attn: John L. Andrews
Attn: Joseph C. Peden/VFSC, Rm. 4230M

General Electric Company
Re-Entry & Environmental Systems Div
P.O. Box 7722
3198 Chestnut St
Philadelphia, PA 19101
Attn: Robert V. Benedict
Attn: John W. Palchefsky Jr.
Attn: Ray E. Anderson

General Electric Company
Ordnance Systems
100 Plastics Ave.
Pittsfield MA 01201
Attn: Joseph J. Reidl

General Electric Company
Tempo-Center for Advanced Studies
816 State St (P O Drawer QQ)
Santa Barbara CA 93102
Attn: Royden R. Rutherford
Attn: DASIAC
Attn: M. Espig

General Electric Company
Aircraft Engine Business Group
Evendale Plant Int Hwy 75 S
Cincinnati OH 45215
Attn: John A. Ellerhorst E2

General Electric Company
Aerospace Electronics Systems
French Road
Utica NY 13503
Attn: Charles M. Hewison/Drop 624
Attn: W. J. Patterson/Drop 233

General Electric Company
P.O. Box 5000
Binghamton NY 13902
Attn: David W. Pepin/Drop 160

General Electric Company-Tempo
c/o Defense Nuclear Agency
Washington DC 20305
Attn: DASIAC
Attn: William Alfonte

General Research Corporation
P.O. Box 3587
Santa Barbara CA 93105
Attn: Robert D. Hill

Georgia Institute of Technology
Georgia Tech Research Institute
Atlanta GA 30332
Attn: R. Curry

Grumman Aerospace Corporation
South Oyster Bay Road
Bethpage NY 11714
Attn: Jerry Rogers/Dept 533

GTE Sylvania, Inc.
Electronics Systems GRP-Eastern Div
77 A St
Needham MA 02194
Attn: Charles A. Thornhill, Librarian
Attn: James A. Waldon
Attn: Leonard L. Blaisdell

GTE Sylvania, Inc.
189 B St
Needham Heights MA 02194
Attn: Paul B. Fredrickson
Attn: Herbert A. Ullman
Attn: H & V Group
Attn: Charles H. Ramsbottom

Gulton Industries, Inc.
Engineered Magnetics Division
13041 Cerise Ave
Hawthorne CA 90250
Attn: Engnmagnetics Div

Harris Corp.
Harris Semiconductor Division
P. O. Box 883
Melbourne, FL 32901
Attn: Wayne E. Abare/MS 16-111
Attn: Carl F. Davis/MS 17-220
Attn: T. L. Clark/MS 4040

Hazeltine Corp.
Pulaski Rd
Greenlawn, NY 11740
Attn: Tech Info Ctr/M. Waite

Honeywell Inc.
Avionics Division
2600 Ridgeway Parkway
Minneapolis, MN 55413
Attn: Ronald R. Johnson/A1622
Attn: R. J. Kell/MS S2572

Honeywell Inc.
Avionics Division
13350 U.S. Highway 19 North
St. Petersburg, FL 33733
Attn: H. H. Noble/MS 725-5A
Attn: S. H. Graaff/MS 725-J

Honeywell Inc.
Radiation Center
2 Forbes Road
Lexington, MA 02173
Attn: Technical Library

Hughes Aircraft Company
Centinela and Teale
Culver City CA 90230
Attn: Dan Binder/MS 6-D147
Attn: Billy W. Campbell/MS 6-E-110
Attn: Kenneth R. Walker/MS D157
Attn: John B. Singletary/MS 6-D133

Hughes Aircraft Co, El Segundo Site
P.O. Box 92919
Los Angeles CA 90009
Attn: William W. Scott/MS A1080
Attn: Edward C. Smith/MS A620

McDonnell Douglas Corp.
3855 Lakewood Boulevard
Long Beach, CA 90846
Attn: Technical Library, C1-290/36-84

Mission Research Corp.
735 State St
Santa Barbara, CA 93101
Attn: William C. Hart

Mission Research Corp. -San Diego
P. O. Box 1209
La Jolla, CA 92038
Attn: V. A. J. Van Lint
Attn: J. P. Raymond

The MITRE Corp.
P. O. Box 208
Bedford, MA 01730
Attn: M. E. Fitzgerald
Attn: Library

National Academy of Sciences
2101 Constitution Ave, NW
Washington DC 20418
Attn: National Materials Advisory Board
Attn: R. S. Shane, Nat Materials Advsy

University of New Mexico
Electrical Engineering & Computer Science Dept
Albuquerque, NM 87131
Attn: Harold Southward

Northrop Corp.
Electronic Division
1 Research Park
Palos Verdes Peninsula, CA 90274
Attn: George H. Towner
Attn: Boyce T. Ahlport

Northrop Corp.
Northrop Research & Technology Ctr
3401 West Broadway
Hawthorne, CA 90250
Attn: Orlie L. Curtis, Jr.
Attn: David N. Pocock
Attn: J. R. Srour

Northrop Corp.
Electronic Division
2301 West 120th St
Hawthorne, CA 90250
Attn: Vincent R. DeMartino
Attn: Joseph D. Russo
Attn: John M. Reynolds

Palisades Inst for Rsch Services Inc
201 Varick St
New York, NY 10014
Attn: Records Supervisor

Physics International Co.
2700 Merced St
San Leandro, CA 94577
Attn: Doc Con for C. H. Stallings

R&D Associates
P. O. Box 9695
Marina Del Rey CA 90291
Attn: S. Clay Rogers

Raytheon Company
Hartwell Road
Bedford, MA 01730
Attn: Gajanan H. Joshi, Radar Sys Lab

Raytheon Company
528 Boston Post Road
Sudbury, MA 01776
Attn: Harold L. Flescher

RCA Corp.
Government Systems Division
Astro Electronics
P. O. Box 800, Locust Corner
Fast Windsor Township
Princeton, NJ 08540
Attn: George J. Brucker

RCA Corporation
Camden Complex
Front & Cooper Sts
Camden, NJ 08012
Attn: E. Van Keuren 13-5-2

Rensselaer Polytechnic Institute
P. O. Box 965
Troy, NY 12181
Attn: Ronald J. Gutmann

Research Triangle Institute
P. O. Box 12194
Research Triangle Park, NC 27709
Attn: Eng Div Mayrant Simons Jr.

Rockwell International Corp.
P. O. Box 3105
Anaheim, CA 92803
Attn: George C. Messenger FB61
Attn: Donald J. Stevens FA70
Attn: K. F. Hull
Attn: N. J. Rudie FA53

IBM Corporation
Route 17C
Owego, NY 13827
Attn: Frank Frankovsky
Attn: Harry W. Mathers/Dept M41

Intl Tel & Telegraph Corp
500 Washington Ave
Nutley NJ 07110
Attn: Alexander T. Richardson

Ion Physics Corp.
South Bedford St
Burlington, MA 01803
Attn: Robert D. Evans

IRT Corp.
P.O. Box 81087
San Diego, CA 92138
Attn: MDC
Attn: Leo D. Cotter
Attn: R. L. Mertz

JAYCOR
205 S. Whitting St, Suite 500
Alexandria, VA 22304
Attn: Catherine Turesko
Attn: Robert Sullivan

Johns Hopkins University
Applied Physics Laboratory
Johns Hopkins Road
Laurel MD 20810
Attn: Peter E. Partridge

Kaman Sciences Corp.
P.O. Box 7463
Colorado Springs, CO 80933
Attn: Jerry I. Lubell
Attn: Walter E. Ware
Attn: John R. Hoffman
Attn: Donald H. Bryce
Attn: Albert P. Bridges

Litton Systems, Inc.
Guidance & Control Systems Division
5500 Canoga Ave
Woodland Hills, CA 91364
Attn: John P. Retzler
Attn: Val J. Ashby/MS 67

Litton Systems, Inc.
Electron Tube Division
1035 Westminster Drive
Williamsport, PA 17701
Attn: Frank J. McCarthy

Lockheed Missiles & Space Co. Inc.
P.O. Box 504
Sunnyvale, CA 94088
Attn: B. T. Kimura/Dept 81-14
Attn: E. A. Smith/Dept 85-85
Attn: George F. Heath/Dept 81-14
Attn: Samuel I. Taimuty/Dept 85-85
Attn: L. Rossi/Dept 81-64

Lockheed Missiles and Space Co. Inc.
3251 Hanover St
Palo Alto, CA 94304
Attn: Tech Info Ctr D/Coll

M.I.T. Lincoln Laboratory
P.O. Box 73
Lexington MA 02173
Attn: Leona Loughlin, Librarian A-082

Martin Marietta Aerospace
Orlando Division
P.O. Box 5837
Orlando, FL 32805
Attn: Jack M. Ashford/MP 537
Attn: William W. Mras/MP 413
Attn: Mona C. Griffith/Lib MP 30

Martin Marietta Corp.
Denver Division
P.O. Box 179
Denver, CO 80201
Attn: Paul G. Kase/Mail 8203
Attn: Research Lib 6617 J. R. McKee
Attn: J. E. Goodwin/Mail 0452
Attn: B. T. Graham/MS PO-454

McDonnell Douglas Corp.
P O Box 516
St Louis, Missouri 63166
Attn: Tom Ender
Attn: Technical Library

McDonnell Douglas Corp.
5301 Bolsa Ave
Huntington Beach, CA 92647
Attn: Stanley Schneider

Rockwell International Corporation
5701 West Imperial Highway
Los Angeles, CA 90009
Attn: T. B. Yates

Rockwell International Corporation
Collins Divisions
400 Collins Road NE
Cedar Rapids, IA 52406
Attn: Dennis Sutherland
Attn: Alan A. Langenfeld
Attn: Mildred A. Blair

Sanders Associates, Inc.
95 Canal St
Nashua, NH 03060
Attn: Moe L. Aitel NCA 1 3236

Science Applications, Inc.
P. O. Box 2351
La Jolla, CA 92038
Attn: J. Robert Beyster
Attn: Larry Scott

Science Applications, Inc.
Huntsville Division
2109 W. Clinton Ave
Suite 700
Huntsville, AL 35805
Attn: Noel R. Byrn

Singer Company (Data Systems)
150 Totowa Road
Wayne, NJ 07470
Attn: Tech Info Center

Sperry Flight Systems Division
Sperry Rand Corp.
P. O. Box 21111
Phoenix, AZ 85036
Attn: Charles L. Craig EV
Attn: Paul Ma fino

Sperry Univac
Univac Park, P. O. Box 3535
St. Paul, MN 55165
Attn: James A. Inda/MS 41T25

Stanford Research Institute
333 Ravenswood Ave
Menlo Park, CA 94025
Attn: Philip J. Dolan

Stanford Research Institute
306 Wynn Drive, N.W.
Huntsville, AL 35805
Attn: MacPherson Morgan

Sundstrand Corp.
4751 Harrison Ave.
Rockford, IL 61101
Attn: Curtis B. White

Systron-Donner Corp.
1090 San Miguel Road
Concord, CA 94518
Attn: Gordon B. Dean
Attn: Harold D. Morris

Texas Instruments, Inc.
P. O. Box 5474
Dallas, TX 75222
Attn: Donald J. Manus/MS 72

Texas Tech University
P. O. Box 5404 North College Station
Lubbock, TX 79417
Attn: Travis L. Simpson

TRW Defense & Space Sys Group
One Space Park
Redondo Beach CA 90278
Attn: Robert M. Webb R1 2410
Attn: Tech Info Center/S1930
Attn: O. E. Adams R1-2036
Attn: R. K. Plebuch R1-2(78

TRW Defense & Space Sys Group
San Bernardino Operations
P. O. Box 1310
San Bernardino, CA 92402
Attn: F. B. Fay
Attn: R. Kitter

United Technologies Corp.
Hamilton Standard Division
Bradley International Airport
Windsor Locks, CT 06069
Attn: Raymond G. Gibuere

Vought Corp.
P. O. Box 5907
Dallas, TX 75222
Attn: Technical Data Ctr

ADDITIONAL DISTRIBUTION LIST

Hanscom AFB MA 01731
Attn: AFGL/SUSRP/Stop 30
Attn: AFGL/CC/Stop 30
Attn: AFGL/SUOL/Stop 20
Attn: ESD/XR/Stop 30
Attn: ESD/XR/Stop 30/D. Brick
Attn: DCD/SATIN IV
Attn: MCAE/Lt. Col. D. Sparks
Attn: ES/Stop 30
Attn: EE/Stop 30

Griffiss AFB NY 13441
Attn: RADC/OC
Attn: RADC/IS
Attn: RADC/DC
Attn: RADC/RB
Attn: RADC/IR
Attn: RADC/CA
Attn: RADC/TIR
Attn: RADC/DAP
Attn: RADC/TILD

Maxwell AFB AL 36112
Attn: AUL/LSE-67-342

US Army Missile Command Labs
Redstone Scientific Information Ctr.
Redstone Arsenal, AL 35809
Attn: Chief, Documents

SAMSO (YA/AT)
P. O. Box 92960
Worldway Postal Center
Los Angeles, CA 90009
Attn: Mr. Hess

Naval Postgraduate School
Superintendent
Monterey, CA 93940
Attn: Library (Code 2124)

U. S. Dept. of Commerce
Boulder Laboratories
Boulder CO 80302
Attn: Library/NOAA/ERL

USAF Academy
Library
Colorado 80840
Attn: 80840

Eglin AFB FL 32542
Attn: ADTC/DLOSL

Scott AFB IL 62225
Attn: AWS/DNTI/Stop 400

NASA Scientific & Technical
Information Facility
P. O. Box 33
College Park, MD 20740

NASA Goddard Space Flight Center
Goddard Space Flight Center
Greenbelt, MD 20771
Attn: Technical Library, Code 252,
Bldg. 21

Naval Surface Weapons Center
White Oak Lab.
Silver Spring, MD 20910
Attn: Library Code 730, RM 1-321

US Naval Missile Center
Point Mugu, CA 93041
Attn: Tech. Library - Code NO322

NASA Johnson Space Center
Attn: JM6, Technical Library
Houston, TX 77058

NASA
Lewis Research Center
21000 Brookpark Road
Cleveland, OH 44135
Attn: Technical Library

Wright-Patterson AFB OH 45433
Attn: AFAL/CA
Attn: AFIT/LD, Bldg. 640, Area B
Attn: ASD/ASFR
Attn: ASD/FTD/ETID

Defense Communications Engineering
Center
1860 Wiehls Ave
Reston, VA 22090
Attn: Code R103R

Director, Technical Information
DARPA
1400 Wilson Blvd.
Arlington, VA 22209

Department of the Navy
800 North Quincy St
Arlington VA 22217
Attn: ONRL Documents, Code 102IP

SAMSO
P. O. Box 92960
Worldway Postal Center
Los Angeles, CA 90006
Attn: Lt. Col. Staubs

US Army Electronics Command
Fort Monmouth, NJ 07703
Attn: AMSEL-GG-TD

Kirtland AFB NM 87117
Attn: AFWL/SUL Technical Library

US Naval Weapons Center
China Lake, CA 93555
Attn: Technical Library

Los Alamos Scientific Lab.
P. O. Box 1663
Los Alamos, NM 87544
Attn: Report Library

Hq DNA
Washington DC 20305
Attn: Technical Library

Secretary of the Air Force
Washington DC 20330
Attn: SAFRD

Scott AFB IL 62225
Attn: ETAC/CB/Stop 825

Andrews AFB
Washington DC 20334
Attn: AFSC/DLC

Army Material Command
Washington DC 20315
Attn: AMCRD

NASA Langley Research Center
Langley Station
Hampton, VA 23365
Attn: Technical Library/MS 185

NASA
Washington DC 20546
Attn: Library (KSA -10)

Andrews AFB
Washington, D.C. 20334
Attn: AFSC/DLS

AFOSR, Bldg. 410
Bolling AFB Washington DC 20332
Attn: CC

AFML
Wright Patterson AFB OH 45433

The Pentagon
Room 3-D-139
Washington, D.C. 20301
Attn: ODDR&E - OSD (Library)

ONR (Library)
Washington, D.C. 20360

Defense Intelligence Agency
Washington, D.C. 20301
Attn: SO-3A

AFAL
Wright-Patterson AFB OH 45433
Attn: WRA-1/Library
Attn: TSR-5/Technical Library

Advisory Group on Electron Devices
201 Varick St, 9th Floor
New York, NY 10014

White Sands Missile Range, NM 88002
Attn: STEWS-AD-L/Technical Library

University of New Mexico
Dept of Campus Security & Police
1821 Roma, NE
Albuquerque, NM 87106
Attn: D. Neaman

METRIC SYSTEM

BASE UNITS:

Quantity	Unit	SI Symbol	Formula
length	metre	m	...
mass	kilogram	kg	...
time	second	s	...
electric current	ampere	A	...
thermodynamic temperature	kelvin	K	...
amount of substance	mole	mol	...
luminous intensity	candela	cd	...

SUPPLEMENTARY UNITS:

Quantity	Unit	SI Symbol	Formula
plane angle	radian	rad	...
solid angle	steradian	sr	...

DERIVED UNITS:

Quantity	Unit	SI Symbol	Formula
Acceleration	metre per second squared	...	m/s
activity (of a radioactive source)	disintegration per second	...	(disintegration)/s
angular acceleration	radian per second squared	...	rad/s
angular velocity	radian per second	...	rad/s
area	square metre	...	m
density	kilogram per cubic metre	...	kg/m
electric capacitance	farad	F	A·s/V
electrical conductance	siemens	S	A/V
electric field strength	volt per metre	...	V/m
electric inductance	henry	H	V·s/A
electric potential difference	volt	V	W/A
electric resistance	ohm		V/A
electromotive force	volt	V	W/A
energy	joule	J	N·m
entropy	joule per kelvin	...	J/K
force	newton	N	kg·m/s
frequency	hertz	Hz	(cycle)/s
illuminance	lux	lx	lm/m
luminance	candela per square metre	...	cd/m
luminous flux	lumen	lm	cd·sr
magnetic field strength	ampere per metre	...	A/m
magnetic flux	weber	Wb	V·s
magnetic flux density	tesla	T	Wb/m
magnetomotive force	ampere	A	...
power	watt	W	J/s
pressure	pascal	Pa	N/m
quantity of electricity	coulomb	C	A·s
quantity of heat	joule	J	N·m
radiant intensity	watt per steradian	...	W/sr
specific heat	joule per kilogram-kelvin	...	J/kg·K
stress	pascal	Pa	N/m
thermal conductivity	watt per metre-kelvin	...	W/m·K
velocity	metre per second	...	m/s
viscosity, dynamic	pascal-second	...	Pa·s
viscosity, kinematic	square metre per second	...	m/s
voltage	volt	V	W/A
volume	cubic metre	...	m
wavenumber	reciprocal metre	...	(wave)/m
work	joule	J	N·m

SI PREFIXES:

Multiplication Factors	Prefix	SI Symbol
$1\,000\,000\,000\,000 = 10^{12}$	tera	T
$1\,000\,000\,000 = 10^{9}$	giga	G
$1\,000\,000 = 10^{6}$	mega	M
$1\,000 = 10^{3}$	kilo	k
$100 = 10^{2}$	hecto*	h
$10 = 10^{1}$	deka*	da
$0.1 = 10^{-1}$	deci*	d
$0.01 = 10^{-2}$	centi*	c
$0.001 = 10^{-3}$	milli	m
$0.000\,001 = 10^{-6}$	micro	μ
$0.000\,000\,001 = 10^{-9}$	nano	n
$0.000\,000\,000\,001 = 10^{-12}$	pico	p
$0.000\,000\,000\,000\,001 = 10^{-15}$	femto	f
$0.000\,000\,000\,000\,000\,001 = 10^{-18}$	atto	a

* To be avoided where possible.

MISSION
of
Rome Air Development Center

RADC plans and conducts research, exploratory and advanced development programs in command, control, and communications (C^3) activities, and in the C^3 areas of information sciences and intelligence. The principal technical mission areas are communications, electromagnetic guidance and control, surveillance of ground and aerospace objects, intelligence data collection and handling, information system technology, ionospheric propagation, solid state sciences, microwave physics and electronic reliability, maintainability and compatibility.

Printed by
United States Air Force
Hanscom AFB, Mass. 01731